Asymmetry of the Diaphragmatic Motion during Vocalization may Cause the Laterality of the Speech Center

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It is unknown why the speech center is located in the left cerebrum. There are no apparent structural asymmetries in organs related to vocalization including the respiratory system. However, beneath the diaphragm, the solid liver is located right, and the deformable air-containing stomach is located left. During vocalization, abdominal muscles contract, elevate the diaphragm through the displacement of those abdominal organs, and control expiratory airflow. We hypothesized that this mechanical asymmetry beneath the diaphragm could be related to the control of vocalization. We investigated diaphragmatic motion with dynamic MR (Magnetic Resonance) images, and found apparent difference between right and left diaphragmatic motions only at the beginning of vocalization, at which left diaphragmatic motions were often paradoxical. Intentional vocal segmentation is thought to be the origin of speech. The speech center in the left cerebrum may be the result that mechanical information of the right diaphragm is preferentially included in the speech circuit.

Key words: Vocalization, Expiratory Airflow, Diaphragm, Abdominal Muscles, Dynamic MRI, Motion Analysis

1. Introduction

Recent comparative neurophysiologic research has revealed that some of finches have song syntax and use their songs as communication tools (Okanoya, 2004). This finding strongly suggests that animal vocalization is the origin of the human language (Okanoya, 2007). Vocalization is performed not only by acoustic source organs such as vocal cords, tongue, and mouth, but also by the respiratory system, a generator of expiratory airflow. However, since there are no apparent structural asymmetries in those organs, it seems impossible to explain the reason why the speech center is located in the left cerebrum in relation to the vocalization function.

The breathing mode during vocalization is different from that at rest (Estenne *et al.*, 1990; Johnston *et al.*, 1993). In the mammal, expiration at rest is performed passively by relaxation of the diaphragmatic muscles. Meanwhile, abdominal muscles work during vocalization so as to control diaphragmatic motion actively and hence to control expiratory airflow rate. There are no apparent asymmetries in the respiratory muscles themselves including abdominal muscles. Although lobe number and lung volume are slightly different between left and right lungs, those differences are thought to be negligible. However, there is an extreme difference in organs beneath the diaphragm between the right and the left sides. There is the liver, a large solid organ, on the right side, and the stomach, a highly deformable air-containing organ, on the left side.

We previously proposed a hypothesis regarding the human upright walk relating to abdominal breathing during vocalization (Kitaoka and Chihara, 2010). We assumed that control of expiratory airflow is the most precisely performed when the air pump was located along the direction of gravity. This assumption explains that singing animals on the earth (songbirds, frogs, rock rabbits, and gibbons) sing at upright posture and that upright walk and language developed simultaneously both in human ontogeny and phylogeny. We have further assumed that there must be mechanical asymmetry in diaphragmatic motion during vocalization and that this asymmetry may cause the laterality of the speech center. In order to partly validate the hypothesis, we investigated diaphragmatic motion during vocalization using dynamic chest MRI.

2. Methods

A normal male volunteer of 58 y/o was subjected to dynamic two dimensional MR (magnetic resonance) imaging under the permission of the ethical committee in Shizuoka City Shizuoka Hospital. Data acquisitions were performed on the frontal section at the center of the thorax (Siemens Magnetom Avanto 1.5T). The body posture was supine. Two image sets were taken at rest and during singing for twenty seconds with 0.5 second interval. Diaphragmatic motion along vertical direction was measured with a sampling line along head-toe direction as shown in Fig. 1. The sampling line was set at the middle of each lung field, and the intersecting point with the diaphragm was plotted over 20 seconds.

3. Results

Plotted graphs of diaphragmatic positions are indicated in Fig. 2. Solid and broken lines are for the right and left sides

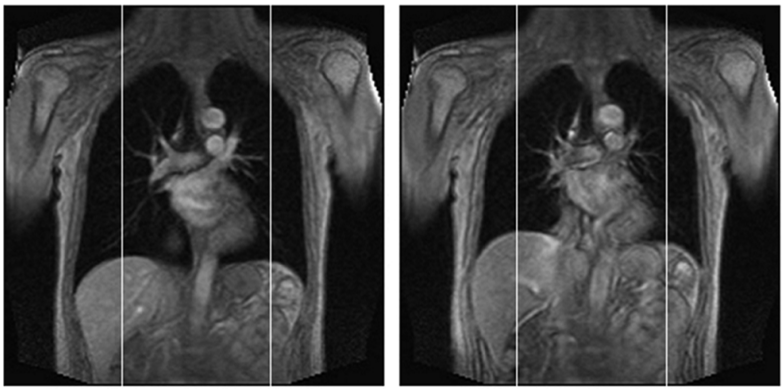

Fig. 1. 2D-MR images during singing at the beginning (left) and the end (right) of vocalization, on the frontal section at the center of the thorax at supine posture. White lines indicate sampling lines for measuring diaphragmatic motion.

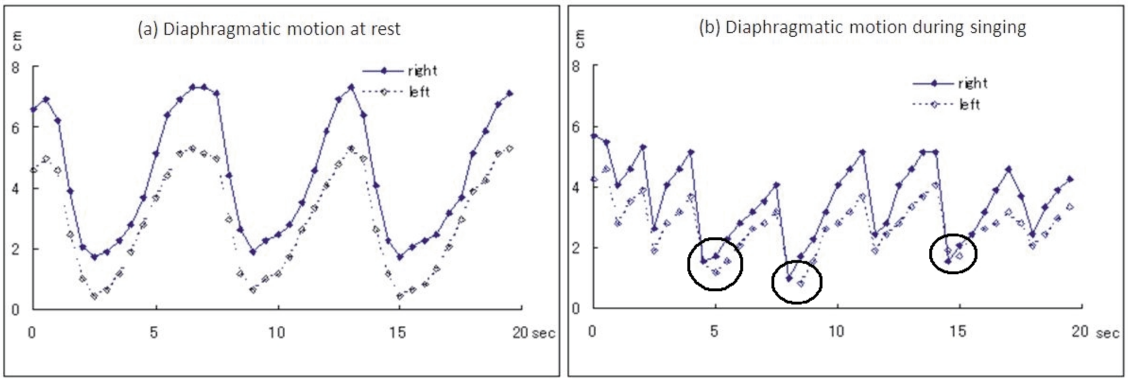

Fig. 2. Diaphragmatic motions at rest (left) and during singing (right). analyzed with dynamic 2D MR images. Intersecting points of sampling lines (white lines in Fig. 1) with the diaphragm were plotted at every 0.5 second.

of the diaphragm, respectively. When the diaphragm is shifted downward, inspiration occurs. Then the diaphragm gradually elevates during expiration. At rest without vocalization (left panel in Fig. 2), bilateral diaphragmatic motions were completely synchronized. Although the left diaphragm was always lower than the right diaphragm with approximately 2 cm difference, the motion was nearly symmetric. On the other hand, paradoxical movements in the left diaphragm were observed during singing. At the beginnings of the third, fourth, and sixth vocalization periods (circles in the right panel in Fig. 2), the left diaphragm further shifted downward in spite that the right diaphragm began to elevate.

4. Discussions

Our experiment indicates that there is apparent asymmetry in the diaphragmatic motion at the beginning of vocalization. Since abdominal muscles work during vocalization, this motion asymmetry is thought to be due to the difference of mechanical transmission of the abdominal muscle power. Through the solid liver, abdominal muscle contraction during vocalization is precisely transmitted to the right lung. On the other hand, it is often incorrectly transmitted to the left lung at the beginning of vocalization due to highly deformable stomach. In addition, the diaphragmatic motion asymmetry does not occur during resting breath because the abdominal muscles do not participate.

Although the experiment was done only under supine posture due to technical limitation, observed phenomenon is thought to be common to all body postures. Recent linguistic research has suggested the origin of syntax may be segmentation of continuous song notes (Suge and Okanoya, 2010). Segmentation of vocalization is to stop and to restart immediately expiratory airflow under cooperative activities of expiratory muscles and acoustic source organs. It is known that affective fibers in the vagal nerve are distributed on the pleura and sense their mechanical distensibilities. Mechanical information of the right pleura is thought to be preferentially included in the speech circuit in order to realize precise control of expiratory airflow.

FOXP2 (forkhead box P2) is so far the only gene implicated in Mendelian forms of human speech and language dysfunction (Lai *et al.*, 2001). A point mutation in *FOXP2* co-segregates with a disorder in a family in which half of the members have severe articulation difficulties accompanied by linguistic and grammatical impairment. The human *FOXP2* protein differs from the gorilla and chimp protein at just two residues, and is shared with Neandeltls (Klause *et al.*, 2007). Knock out experiments revealed that loss of *FOXP2* in mice leads to defective postnatal lung alveolarization as well as brain development disorder (Shu *et al.*, 2007). Comparison between the chimpanzee and the human has revealed that the two human-specific amino acids alter *FOXP2* function by conferring differential transcriptional regulation (Konopka *et al.*, 2009). According to our experiment regarding diaphragmatic motion, there is a possibility that targeted genes by human *FOXP2* may be related to control of the diaphragmatic motion.

5. Conclusions

Our hypothesis was partly verified by dynamic chest MR imaging. Future investigations using advanced neurofunctional imaging techniques will reveal relationships between the diaphragmatic motion, abdominal muscle activity, and linguistic functions. Ancient Greek people believed that the human mind was located at the diaphragm (=phrene). This idea had disappeared in the modern Western medicine except the nomenclature of "Schizophrenia". Vocalization is the most straightforward expression of the human spirit. Ancient Greek people might have known the true significance of diaphragmatic motion.

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